NEW SPACE-BORNE SENSORS FOR OIL SPILL RESPONSE

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ABSTRACT: *In the next few years, several new satellite sensors will be launched by various national remote-sensing/earth observation agencies around the globe. It is hoped that these space-borne sensors will provide oil spill response personnel with more than just a synoptic overview of the spill scene. The state-of-the-art capabilities of these new sensors should provide responders with information that can be used in a tactical role as opposed to older-generation sensors that perform a strictly strategic role. Of primary use to spill response coordinators is the Synthetic Aperture Radar (SAR) sensor. The next generation of SAR satellites will have enhanced capabilities when compared to their predecessors. The enhancements include the addition of polarimetric modes for satellites, including Envisat-1 and RADARSAT-2. RADARSAT-2 will be quad-polarimetric, with resolutions of 8 × 8 m in polarimetric mode and down to 3 × 3 m in co- or cross-pole modes. The ASAR sensor on Envisat-1 will follow up the successful missions of the European Space Agencies ERS-1, -2 satellites. ASAR will have an alternating polarization mode, and transmit and receive polarization can be selected, thus allowing scenes to be imaged simultaneously in two polarizations. In addition to SAR satellites, several new optical satellites have been or will be launched over the next few years. While optical sensors often are plagued by periods of foul weather that frequently accompany oil spills, some of these sensors will provide valuable information that can be used in conjunction with the radar data in a corroborative fashion. The most useful of the new optical satellites might well be those used to collect data for weather forecasting.*

This paper will review the operating characteristics and modes of recent and planned satellite sensors, with an eye toward their usefulness for tactical remote sensing of oil spills.

Introduction

In response to a major oil spill, there are requirements for both long-term and short-term goals. In terms of remote-sensing capabilities, airborne sensors traditionally have addressed tactical or short-term needs. A survey of marine surveillance and remote-sensing organizations around the world supports this generalization (Brown and Fingas, 1999). Oil spills inherently are dynamic in nature, as the oil is affected by the physical environment in which it is spilled and its own changing chemical composition. Prompt information about the location and extent of the spill is required to direct spill countermeasures effectively. Often information that is more than a few hours old is useless except for purposes of documentation. Certain specific types of sensors are not yet available (nor will they be in the foreseeable future) on space-borne platforms. These sensors include infrared sensors and laser fluorosensors that are affected adversely by the extremely long path lengths and atmospheric absorption and scattering processes. These sensors are useful from a tactical perspective in that they can help detect and classify oil extremely well in real time. They are not, however, wide field-of-view (FOV) sensors and therefore do not provide the synoptic view of the overall spill area. In addition, these sensors are susceptible to foul weather.

Spatial resolution requirements vary but should be considered even for massive oil spills. It is well known that spills at sea form windrows with widths often less than 10 m. A spatial resolution of greater than this is required to detect these spills. Furthermore, when considering oil spills, information often is required on a relatively short timescale to be useful to spill response personnel. The spatial and temporal requirements for oil spills depend on what use would be given to the data. Table 1 estimates spatial and time requirements for several oil tasks.

Table 1.

Task	Minimum resolution requirements		Maximum time during which useful data can be collected (h)
	Large spill (m)	Small spill (m)	
Detect oil on water	6	2	1
Map oil on water	10	2	12
Map oil on land/shore	1	0.5	12
Tactical water cleanup support	1	1	1
Tactical support land/shore	1	0.5	1
Thickness/volume measurement	1	0.5	1
Legal and prosecution	3	1	6
General documentation	3	1	1
Long-range surveillance	10	2	1

Note: Adapted from Fingas *et al.* (1998).

Radar and microwave sensors

Over the past decade a number of remote sensors have been placed on earth observation satellites. Of particular interest is the development of Synthetic Aperture Radars (SARs) for deployment on satellite platforms. Oil on the sea surface dampens some of the small capillary waves that normally are present on clean seas. These capillary waves reflect radar energy producing a "bright" area in radar imagery known as sea clutter. The presence of an oil slick can be detected as a "dark" area or one with an absence of sea clutter. Unfortunately, oil slicks are not the only phenomenon that can be detected in similar manner. There are many potential interferences including fresh water slicks, calm areas (wind slicks), wave shadows behind land or structures, vegetation or weed beds that calm the water just above them, glacial flour, biogenic oils, and whale and fish sperm. SAR satellite imagery has shown that several false signals are present in a large number of scenes (Bern *et al*., 1993; Wahl *et al.*, 1993).

Despite these limitations, radar is an important tool for oil spill remote sensing since it is the only sensor capable of searching large areas. Radars, being active sensors operating in the microwave region of the electromagnetic spectrum, are one of the few sensors that can "see" at night and through clouds or fog. Experimental work on oil spills has shown that X-band radar yields better data than L- or C-band radar (Fingas and Brown, 1996). Furthermore, it has been shown that antenna polarizations of vertical for transmission and vertical for reception (VV) also yield better results than other configurations (Alpers and Hühnerfuss, 1989; Madsen *et al.*, 1994). Recent investigations have found that C-band HH polarized imagery, such as that collected with the RADARSAT-1 satellite, does an extremely good job on delineating oil slicks (Vachon and Olsen, 1998). Radar detection of oil slicks is limited by sea state; low sea states will not produce sufficient sea clutter in the surrounding sea to contrast to the oil, and very high seas will scatter radar sufficiently to block detection inside the troughs. Indications are that wind speeds of at least 1.5 m/s (~3 knots) are required as a minimum to allow detection, and a maximum of 6 m/s will again remove the effect (Hielm, 1989; Hühnerfuss *et al.*, 1989). This limits the application of radar for oil slick detection.

In the past few years, these SAR satellites have provided useful imagery for a number of large marine oil spills, including *Sea Empress*, *Braer*, and *Nakhodka*. The spatial resolution and revisit times afforded by these SAR satellites historically has relegated their use as strategic as opposed to tactical tools. Table 2 lists the spatial resolutions, swath widths, and over pass frequencies of selected space-borne and airborne sensors.

To be more useful to the spill response community, the operating characteristics of space-borne satellites need to resemble those of airborne sensors more closely. While this is not always technologically feasible, planned improvements in the capabilities of satellite remote sensors will narrow the gap with respect to airborne sensors. Of optimum importance is the frequency of data collection, processing time, and the inherent spatial resolution of the imagery provided. There are two ways to increase the frequency of data collection: firstly, by increasing the number of satellites available and secondly, by launching satellites that have sensors that can be steered or aimed at the target of interest.

Over the next few years, technologically advanced space-borne SAR sensors are scheduled to be launched by the European Space Agency (ASAR Advanced Synthetic Aperture Radar, C-band, on Envisat), Canada (RADARSAT-2, C-band), and the National Space Development Agency of Japan (PALSAR, the Phased Array type L-band Synthetic Aperture Radar on ALOS). Each of these three planned SAR sensors have various degrees of steerage and provide ScanSAR mode capabilities. ScanSAR radar illuminates several adjacent ground swaths almost simultaneously by "scanning" the radar beam across a large area in a rapid sequence. The adjacent scenes (which are typically 50 km in width) are then merged into a single large scene during processing.

In addition to improved data frequency and spatial resolution, these SAR sensors offer enhanced polarization capabilities. One might expect the enhanced polarimetric capabilities of these new SAR sensors will help reduce the number of false targets in SAR imagery. It is reasonable to expect that certain of the physical or biogenic processes that cause "slick-like" features in SAR imagery will appear different in polarimetric imagery than actual oil slicks. Experimental confirmation of this theory will be required. The capabilities of these three SAR sensors are provided in Tables 3, 4, and 5. Examination of these tables reveals the improving spatial resolution offered by these new SAR satellites is beginning to approach that of airborne SAR systems. One pitfall of these advanced SAR satellites is that the technology employed is state-of-the-art and has created delays in the sensor production and satellite launches. Therefore, when the satellites finally are launched, they are not increasing the number of available satellites as their predecessors have often ended their useful lifetimes.

Table 2.

	Spatial resolution		Swath width	Over pass frequency	Full-earth repeat cycle	Process time	
	Minimum	Range				Minimum	Typical
Radar							
ERS-1	30 m		100/500 km	3 days	35 days	5 hours	2 days
ERS-2	30 m		100/500 km	3 days	35 days	5 hours	2 days
RADARSAT-1	9 m	9–100 m	50–500 km	2 days	7/17 days	5 hours	2 days
Airborne sensors							
Typical SLAR	10 m	10–50 m	10–30 km	As required		Real time	Real time
Typical SAR	1–3 m	1–10 m	10–30 m	As required		Real time	Real time
Optical							
Landsat TM	15 m	15–120 m	185 km		16 days	12 hours	3 days
SPOT	10 m		60/85 km		26 days	12 hours	3 days
Airborne sensors							
Video camera	<1m	Altitude dependant		As required		Real time	Real time
Still camera	<0.1m	Altitude dependant		As required		1 hour	1 day
Typical scanner	<1m	Altitude dependant		As required		Real time	Real time

Note: Adapted from Fingas *et al.* (1998).

Table 3.

Observation mode	Global monitoring	Image mode	Alternating polarization	Wide swath (ScanSAR)
Frequency			C-band	
Polarization	HH or VV	HH or VV	HH/VV or HH/HV or VV/VH	HH or VV
Spatial resolution	1,000 m	30 m	30 m	150 m
Swath width	405 km	58–109 km	58–109 km	405 km
Incidence angle		15–45 degrees	15–45 degrees	

Table 4.

Standard and Wide Swath Modes *					
Beams/Modes	Low Incidence	Standard		High Incidence	Wide Swath
		1 to 2	3 to 7		
Resolution	25m x 35 m	25m x 25 m		20m x 25m	25m x 35m
Swath Width	170 km	100 km	100 km	70 to 80 km	120 to 170 km
Incidence Angles	10 to 23°	20 to 31°	30 to 49°	49 to 59°	20 to 45°
Bandwidth	17 MHz	17 MHz	12 MHz	12 MHz	12 MHz
Polarization	co- and/or cross-polar				

Polarimetric		
Beams/Modes	Standard Quad-Polarization	Fine Quad-Polarization
Resolution	25m x 25m	8m x 8m
Swath Width	25 to 50 km	25 to 50 km
Incidence Angles	20 to 41°	20 to 41°
Bandwidth	12 or 17 MHz	26 MHz
Polarization	Quad-Polar	

Fine Resolution			
Beams/Modes	Fine	Triple Fine	Ultra-Fine
Resolution	8m x 8m	8m x 3m	3m x 3m
Swath Width	50 km		
Incidence Angles	30 to 50°	30 to 50°	30 to 50°
Bandwidth	26 MHz	100 MHz	100 MHz
Polarization	co- and/or cross-polar	co- or cross-polar	

ScanSAR *				
Beams/Modes	ScanSAR Narrow A	ScanSAR Narrow B	ScanSAR Wide A	ScanSAR Wide B
Resolution	50m x 50 m		100m x 100m	
# Beams	2	3	4	4
Total Width	310 km	300 km	530 km	460 km
Incidence Angles	20 to 40°	31 to 47°	20 to 49°	20 to 47°
Bandwidth	12 MHz	12 MHz	12 MHz	12 MHz
Polarization	co- and/or cross-polar			

* Standard modes are approximately 108 km wide and the incidence angle varies from 20 to 49 degrees as one moves from S1 to S7. ScanSAR modes are large swath modes, with Narrow being approximately 300 km in width and Wide being approximately 500 km in width. The resolution in Narrow and Wide ScanSAR modes is approximately 50 and 100 m respectively.

Table 5. Major specifications of PALSAR.

Observation Mode	Fine Resolution	ScanSAR Mode
Frequency	L-band	
Polarization	HH or VV (option: HV or VH)	
Spatial Resolution	10 m (2 looks) 20 m (4 looks)	100 m
Swath Width	70 km	250 - 360 km
Off-nadir Angle	18 - 48 degrees	
S/A	25 dB	
NEσ°	-25 dB	

Note: From NASDA; available on-line at *http://yyy.tksc.nasda.go.jp/Home/Earth_Obs/e/alos_e.html*.

The timeliness of remotely sensed data is extremely important from a spill response point of view. There are technical limitations related to the tasking of satellites to image a particular area on the surface of the earth. Tasking of these satellites is generally done twice daily (i.e., once per satellite pass), and this is a "fixed" parameter. Satellite providers, however, are working to reduce the amount of time required to task their satellites in the event of an emergency such as a major oil spill. Efforts also are being made to improve the speed with which SAR data is processed to produce final useable imagery and the speed with which it is delivered to response organizations (e.g., compressed data via the Internet).

Of particular importance when responding to major oil spills is the ability to predict or model the trajectory of the slick to protect sensitive coastal environments. The ability to model this movement requires knowledge of the slick spatial size, quantity of oil involved, weathering properties of the oil, and environmental conditions such as wind speed and direction. Satellite remote sensors can provide information for many of these environmental conditions. The movement of surface oil slicks is affected for the most part by ocean currents and to some extent by the wind (generally about 3%). This is a composite effect, with the net surface velocity being the vector sum of the two. While ocean current information can be obtained from nearshore buoy-mounted sensors, this is not the case for offshore spills. Some of this information can be interpreted from visible and SAR imagery. The Spacecraft Engineering Department of the U.S. Navy is developing a multi-frequency polarimetric microwave radiometer (known as WindSat) for measuring ocean surface wind speed and direction[1]. This sensor is to demonstrate the viability of the technique and to provide tactical information to Navy units; however, if the system is successful, there may be opportunity for civilian use in the future. The horizontal resolution of the WindSat radiometer will be 25 km, with a mapping accuracy of 5 km. Wind speeds will be measured from 3 to 25 m/s (precision 1 m/s) and directions from 0 to 360 degrees (precision10 degrees).

Visible sensors

Oil has an increased surface reflectance above that of water in the visible (400 to 700 nm), but shows limited non-specific absorption tendencies. In the visible region of the electromagnetic spectrum, oil has no sharp spectral features, and hence appears black, brown, or gray to the observer. Sheen appears silvery and reflects light over a wide region up to the blue. There is no characteristic information in the visible region between 500 and 600 nm, so this region often is filtered out to provide increased contrast. In general, oil has no spectral characteristics in the visible band that distinguish it from the background. Taylor (1992) examined the visible spectra of oil in the laboratory and field, and observed flat spectra with no spectral features that could be employed to distinguish it from the background. R. Neville (*Private communication*, 1994) has proposed that contrast between oil and background increases with increasing wavelength. Experimentally it has been found that the use of a horizontally aligned polarizing filter, which passes only that light reflected from the water surface and setting the camera at Brewster's angle (53 degrees from vertical), improves the contrast in visible imagery. It is this component that contains the information on surface oil (O'Neil *et al.*, 1983). This technique is said to increase contrast by as much as 100%. Filters that have band-pass below 450 nm also can be used to improve contrast. One should recognize the likelihood that the recognition of oil in the visible spectrum may be more related to human pattern recognition than color.

The use of visible techniques generally is restricted to that of documentation because the lack of a positive oil detection mechanism. In addition, many interferences or false positives such as sun glint and wind slicks can be mistaken for oil sheens. Biogenic material such as surface vegetation or sunken kelp also can be mistaken for oil.

Major oil spills often occur as the result of extreme weather conditions. These same extreme weather conditions often include heavy rain, fog, and clouds, which can prevent the collection of visible imagery in the vicinity of the slick. Nevertheless, if visible imagery is available, it can be superimposed onto or compared with SAR imagery to provide clues as to the location of false targets (areas that appear to be oil slicks but in fact are not). Some of this visible imagery can point to locations of oceanic fronts, thermoclines, etc. that have been mistaken for oil slicks. Imagery from weather satellites also could be compared to and combined with SAR imagery to help differentiate between false targets and true oil slicks. Satellites such as the Geostationary Operational Environmental Satellite (GOES) can provide near *real time* visible (during daylight hours) and thermal infrared imagery from fixed orbits twice hourly. While the spatial resolution of these images is very coarse, it can provide indications of environmental anomalies that can be mistaken for oil slicks. These data often are available free of charge via the Internet.

There are several new high-resolution visible sensors being developed for launch aboard space-borne platforms in the upcoming years. Both commercial enterprises and the scientific community through various national space agencies are developing these sensors. The resolution of some of these new systems is on the order of 1 to 2.5 m compared to the 10 to 20 m that have been available until recently. The European Space Agency is launching the Medium Resolution Imaging Spectrometer (MERIS) onboard the Envisat Earth Observation Satellite[2]. MERIS is designed to map ocean color over open ocean and coastal zone waters using 15 bands in the visible to near infrared from 412.5 to 900 nm. MERIS will provide information on suspended sediments, ocean thermal features, and biogenic phenomena related to chlorophyll production and algal blooms. The spatial resolution of MERIS is rather coarse at 300 m, but when used in conjunction with SAR data could prove useful in response to oil spills.

While details of all commercial satellites due for launch is beyond the scope of this paper, brief details of a few of the systems are presented within. Readers are encouraged to contact commercial data providers to learn more details of present and future satellite sensors. High-resolution imagery (1 m panchromatic, 4 m multi-spectral) is now available from systems such as the Ikonos satellite[3]. Unfortunately, while this imagery is inexpensive, delivery is on the order of a few days hence not of much use for tactical oil spill response. ORBIMAGE will launch two high-resolution multi-spectral imaging satellites in mid-2001[4]. The OrbView-3 and -4 satellites will provide 1 m panchromatic and 4 m multi-spectral imagery with a swath-width of 8 km that can be downloaded in real time to satellite receiving stations. In addition, OrbView-4 will provide 200-channel hyperspectral imagery with a swath width of 5 km. Details of these two satellites are provided in Table 6. Multi-spectral and panchromatic imagery has been available from the SPOT satellites for a number of years now. The imagery is currently available at 10 m (panchromatic) and 20 m (multi-spectral) spatial resolutions. The next generation SPOT-5 satellite will improve this resolution to 2.5–5 m. Certain characteristics of the existing and planned SPOT series of satellite sensors are listed in Table 7. Contact information for satellite controlling agencies can be found on the Internet[5].

Table 6. OrbView future satellite specifications.

Satellite	OrbView-3		OrbView-4		
Imaging mode	**Multispectral**	**Panchromatic**	**Multispectral**	**Panchromatic**	**Hyperspectral**
Spatial resolution (m)	4	1	4	1	8
# imaging channels	4	1	4	1	200
Spectral range (mm)	450 to 520 520 to 600 625 to 695 760 to 900	450 to 900	450 to 520 520 to 600 625 to 695 760 to 900	450 to 900	450 to 2500
Swath width (km)		8		8	5
Image area (km^2)		64		64	25
Revisit time	Less than 3 days				

Table 7. Technical Data SPOT Satellites

Satellite	SPOT 1,2,3		SPOT 4		SPOT 5 (2002)	
Imaging mode	**Multispectral**	**Panchromatic**	**Multispectral**	**Panchromatic**	**Multispectral**	**Panchromatic**
Spectral Bands (µm)	0.50 to 0.59 0.61 to 0.68 0.79 to 0.89	0.51 to 0.73	0.50 to 0.59 0.61 to 0.68 0.79 to 0.89 1.58 to 1.75	0.61 to 0.68		
Pixel Size (m)	20 x 20	10 x 10	20 x 20	10 x 10	10 x 10 (shortwave IR 20 x 20)	5 x 5 2.5 x 2.5
Swath Width (km)	60	60	60	60	60	60

Note: From SPOT; available on-line from *http://www.spotimage.fr/home/system/introsat/seltec.htm* and *http://www.spotimage.fr/home/system/future/spot5/spot5.htm*.

Conclusions

Several new satellite sensors will be launched in the next few years by various national remote sensing/earth observation agencies around the globe. These space-borne sensors will provide oil spill response personnel with more precise and timely information rather than just a synoptic overview of the spill scene. The state-of-the-art capabilities of these new sensors should provide responders with information that can be used for tactical remote sensing of oil spills. The most useful of these new generation satellites will likely be the SAR satellites. In addition to the SAR satellites, several new optical satellites have been or will be launched over the next few years. While optical sensors are often plagued by periods of foul weather, which frequently accompanies oil spills, these sensors will provide valuable information that can be used in conjunction with the SAR data in a corroborative fashion.

Biography

Carl Brown is a scientist working in oil spill remote-sensing research and development. His specialties include airborne oil spill sensor development and the application of laser technologies to environmental problems. He has a doctorate degree in physical chemistry and a bachelor of technology degree. He has authored over 80 papers and publications.

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[1] From Spacecraft Engineering Department, U.S. Naval Research Laboratory; available on-line at *http://www.pxi.com/windsat/descript.html*)

[2] From ESA; available on-line at *http://envisat.estec.esa.nl/instruments/meris/index.html*)

[3] From Space Imaging Incorporated; available on-line at *http://www.spaceimaging.com/carterra/geo/prodinfo/geotech.htm.*

[4] From Orbital Imaging Corporation; available on-line at *http://www.orbimage.com/satellite/satellite.html*.

[5] From Canada Centre for Remoste Sensing and Canadian Space Agency; available on-line at *http://www.ccrs.nrcan.gc.ca/ccrs/comvnts/misc/agencie.html* and *http://www.space.gc.ca/space/related_sites/other_spa_agencies/default.asp*, respectively.